BREAKTHROUGHS IN LOW-PROFILE LEAKY-WAVE HPM ANTENNAS

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21 Sep 2016

Data Item: A002 - Progress, Status, & Management Quarterly Report #12

Prepared for:

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ONR Code 30

OFFICE OF NAVAL RESEARCH
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Arlington, VA 22203-1995

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
21-09-2016

2. REPORT TYPE
Quarterly

3. DATES COVERED *(From - To)*
22 Jun 2016 – 20 Sep 2016

4. TITLE AND SUBTITLE
Breakthroughs in Low-Profile Leaky-Wave HPM Antennas
Progress, Status, & Management Report
(Quarterly Report #12)

5a. CONTRACT NUMBER
N00014-13-C-0352

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Koslover, Robert A.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Scientific Applications &
Research Associates, Inc.
6300 Gateway Drive
Cypress, CA 90630-4844

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
875 North Randolph Street
Suite 1425
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
Code 30

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution Statement A. Approved for public release; distribution is unlimited. Other requests for this document shall be referred to the Program Officer listed in the contract.

13. SUPPLEMENTARY NOTES
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14. ABSTRACT
This report describes progress made during the 12th quarter of this R&D program and highlights the current status of the research. We are especially pleased to report that during this period we developed a significantly-improved design for the "Rotated Aperture Waveguide Sidewall-Emitting Antenna" (RAWSEA). The new design offers two key advantages over its predecessors: (1) a lower profile (shallower depth) than any of the other HPM-capable leaky-wave antennas investigated under this program, even including previous shallow-depth RAWSEAs; and (2) a simplified design procedure for the leaky-wave grill. Note: This is the last of the periodic Quarterly Reports to be submitted by SARA under the overall 37-month program. The Final Report (due next month) is currently under preparation.

15. SUBJECT TERMS
Leaky-wave Antennas. High Power Microwaves (HPM) Antennas. Low-profile Conformal Antennas.

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
					Lee Mastroianni
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER**(incl. area code)
Unclassified	Unclassified	Unclassified	SAR	___	(703) 696-3073

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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1. INTRODUCTION

This is SARA's 12th Quarterly Report for "Breakthroughs in Low-profile Leaky-Wave HPM Antennas," a 37-month Basic Research effort sponsored by the US Office of Naval Research (ONR). This work includes fundamental theoretical analyses, numerical modeling, and related basic research. Objectives include to discover, identify, investigate, characterize, quantify, and document the performance, behavior, and design of innovative High Power Microwave (HPM, GW-class) antennas of the *forward-traveling*, *fast-wave*, *leaky-wave* class.

1.1. Overview of Previous Activities (1st thru 11th Quarter)

During the *first* quarter, we prepared and established useful equations and algorithms for predicting reflections and transmission of incident TE waves from parallel-wire grills, dielectric windows, and combinations of wire grills with dielectric windows, in problems reducible to purely H-plane (2D) representations. We then applied this theory to guide the design of high-gain configurations (again, limited to 2D, H-plane representations) for linear, forward traveling-wave, leaky-wave antennas. The theory built upon equivalent circuit methods and wave matrix theory, which provided useful formalisms upon which we continue to build.

During the *second* quarter, we pursued initial extensions of the previous work into three dimensions, in order to include phenomena with E-plane dependencies. We succeeded in adding into the wave-matrix formalism the reflection/transmission properties associated with the transition to free space from a *finite-width* leaky-wave channel, including the edge-tapering essential to HPM applications. These geometric aspects do not arise in analyses confined to the H-plane alone. Our 3D analyses were somewhat more reliant on numerical models than in the 2D analyses, due to the greater complexity of identifying and/or building practical analytic approaches capable of addressing true 3D geometries of interest.

During the *third* quarter, we explored channel-to-channel coupling (aka, mutual coupling) which (as we have noted earlier) is an important design concern, since it can impact antenna performance significantly in terms of gain, peak power-handling, and impedance matching. Our approach leveraged mostly numerical methods, along with some intuitive arguments, as we explored designs exhibiting different degrees of mutual coupling between adjacent channels. As past and current antenna literature attest, mutual coupling analyses are non-trivial; suffice to say, there is still much work to be done in this area.

During the *fourth* quarter, we continued to study and employ wave-matrix based methods, but with less success than before in applying this approach to *improve* or *optimize* the initial designs. The formalism itself is still valid, but offers reduced practical rewards once an *initial* (i.e., not fully-optimized) geometry (e.g., grill, window, channel depth, etc.) is derived from the more basic-level principles. At that stage, we are finding that further optimization is currently best proceeding via numerical means. Additional work in the fourth quarter led us to identify *new aperture geometries* of potentially-significant practical value, which included the "BAWSEA" and "GAWSEA". These configurations may significantly extend the utility of leaky-wave antenna technology to support integration on more challenging platforms.

During the *fifth* quarter, we designed, analyzed, and documented representative high-performance FAWSEA and CAWSEA antennas suitable for designation as "standard" or "recommended." The configurations we described were scalable with wavelength. These are the initial entries in a library of antennas that will continue to be built throughout this program.

During the *sixth* quarter, we performed additional investigation of designs to support the newer curved apertures, especially the "Bent Aperture Waveguide Sidewall-emitting Antenna" (BAWSEA). We presented this work at the 17th Annual Directed Energy Professional Society (DEPS) Symposium in Anaheim, CA, on March 4th, 2015. Our full slide presentation, entitled "Advances in Low-Profile Leaky-Wave Conformable Antennas for HPM Applications," was included in the unclassified proceedings CD that was recently distributed by DEPS to all the conference attendees.

During the *seventh* quarter, we investigated RAWSEA design considerations and showed that the angle of rotation between the leaky wave channels and the aperture can be understood in terms of an equivalent linear (non-rotated) displacement, an interpretation which helps to guide application of the wave-matrix formalism. However, more work is still needed to speed-up the RAWSEA design process.

During the *eighth* quarter, we identified, investigated, and applied a seemingly-simple but clarifying wave-mapping methodology, which provided improved guidance in making optimal use of generally curved platform surfaces. Following this process helps guide the designer toward a solution that provides both higher gain and greater peak power handling. Via this approach we identified and reported a notable success with the design of an improved CAWSEA that can deliver superior gain, yet still conform to the same radius cylinder as our earlier-suggested "standard/recommended" design.

During the *ninth* quarter, we developed/extended the ray-based analyses to the AAWSEA configuration, employing an analytic parameterization of the inner-curve (channel back-wall) and outer-curve (vicinity of the leaky-grill wall) ogives, while tracking the varying angles of reflection sequentially along the perspective leaky guide, and ultimately adjusting these curves to yield the desired output beam. The approach offered insight, but did not lead us to design recipes with a practical utility comparable to those for the FAWSEA or CAWSEA.

During the *tenth* quarter, we continued to investigate design methods for the AAWSEA and explored new and novel applications/extensions to HPM leaky-wave antenna technology. We presented our work at the DEPS 18th Annual Directed Energy Symposium. Our presentation also included concepts for the use of GW-capable FAWSEA or CAWSEA-type *feeds* to drive larger *conical* dish reflectors. Combining such a FAWSEA/CAWSEA feed with a *conical* trans-reflector and a flat twist-reflector (a configuration which is now patent pending) yields, to the best our knowledge, *the world's first and only <u>GW-class</u>, <u>fully-steerable</u>, <u>high-gain</u> antenna*. Also during the tenth quarter, we began to explore ways to *suppress beam-scanning* with frequency, to see if broader-bandwidth HPM-capable antennas leveraging leaky-wave structures could be realized.

During the *eleventh* quarter, we extended our analyses of the AAWSEA and documented a suggested/ recommended 3D AAWSEA design, along with performance predictions. We also identified, designed, and analyzed a novel cylindrical leaky-wave high-gain HPM-capable antenna that can be directly-connected, without requiring mode-conversion, to cylindrical-type HPM-sources with TM_{01}-circular mode outputs. This concept expands the applicability of HPM-capable leaky-wave antennas to a number of HPM source/platform combinations that might not otherwise be practical. We also achieved success in establishing a novel design for a related antenna geometry that compensates for the frequency-scanning characteristics of these types of antennas, yielding a *fixed-direction* high-gain beam as the frequency is varied across a substantial bandwidth.

For more information, we encourage the reader to refer to our earlier *Quarterly Reports #1* thru *#11.*

1.2. Overview of Recent Activities (12th Quarter)

We are pleased to report that during this final full quarter of the subject R&D program, we achieved yet another technical advance – establishing an even *lower-profile* (shallower-depth) configuration than any of our previous designs. The basic idea of reducing the FAWSEA-type antenna profile by rotating the multiple parallel leaky-wave channels relative to the aperture goes back to SARA's work during early September, 2012. At the time, we identified this configuration as the "Rotated Aperture Waveguide Sidewall-Emitting Antenna" (RAWSEA). The reduction in depth achievable via rotating the channels, though significant, was limited by the channels bumping against one another if the angle was increased too far. However, in our new design, by re-positioning the leaky-grill to its pre-rotation position, we can employ shallower depth channels, and have room to achieve a full 90^{o} rotation of the channels without interfering with neighboring channels. This change yields an even shallower-depth package, without significantly compromising performance. In addition, the required leaky-grill and window design can

then be borrowed, with minimal modification, from our earlier designs with non-rotated channels. This change also effectively avoids/bypasses the complexity of the leaky-grill design challenge for RAWSEAs that was identified in our 7th Quarterly Report. Example 3D RF models and performance predictions for a flat version of this new and improved low-profile design (referred to now as the "Flat Rotated Aperture Waveguide Sidewall-Emitting Antenna" or FRAWSEA) are documented in in Section 3. In accordance with our earlier naming convention, Curved (CRAWSEA), Bent (BRAWSEA), and Arched (ARAWSEA) versions that incorporate this new design feature should also be possible.

Some results of research performed under this program were presented by SARA at the 17th and 18th Annual Directed Energy Symposia sponsored by the Directed Energy Professional Society (DEPS) in 2015 and 2016, respectively. We also recently submitted an abstract (approved for public release by ONR) for another presentation to be given at the upcoming URSI National Radio Science Meeting (NRSM) to be held on January 4-6, 2017 in Boulder, CO.

2. STATUS OF THE PLAN/SCHEDULE AND FUNDING

Figure 1 (next page) maps out the updated program plan, for quick reference. The subject contract was awarded on 9/18/2013 and has an end date of 10/17/2016. The total contract value is $868,350, all of which was authorized per P00006, dated 6/23/2015.

According to SARA's accounting system, as of Sept 16, 2016, expenses and commitments (including fee) totaled $848,366, thus leaving $19,984 in available funds. If one simply compares the calendar and spending on this project, we have now consumed ~97.3% of the calendar and ~97.7% of the total contract value. Remaining contract funds are being devoted to preparation of the Final Report and any other required documentation.

Again, we wish to thank ONR for the past and continued support of this project. There are no significant technical, schedule, or funding-related program problems to report at this time.

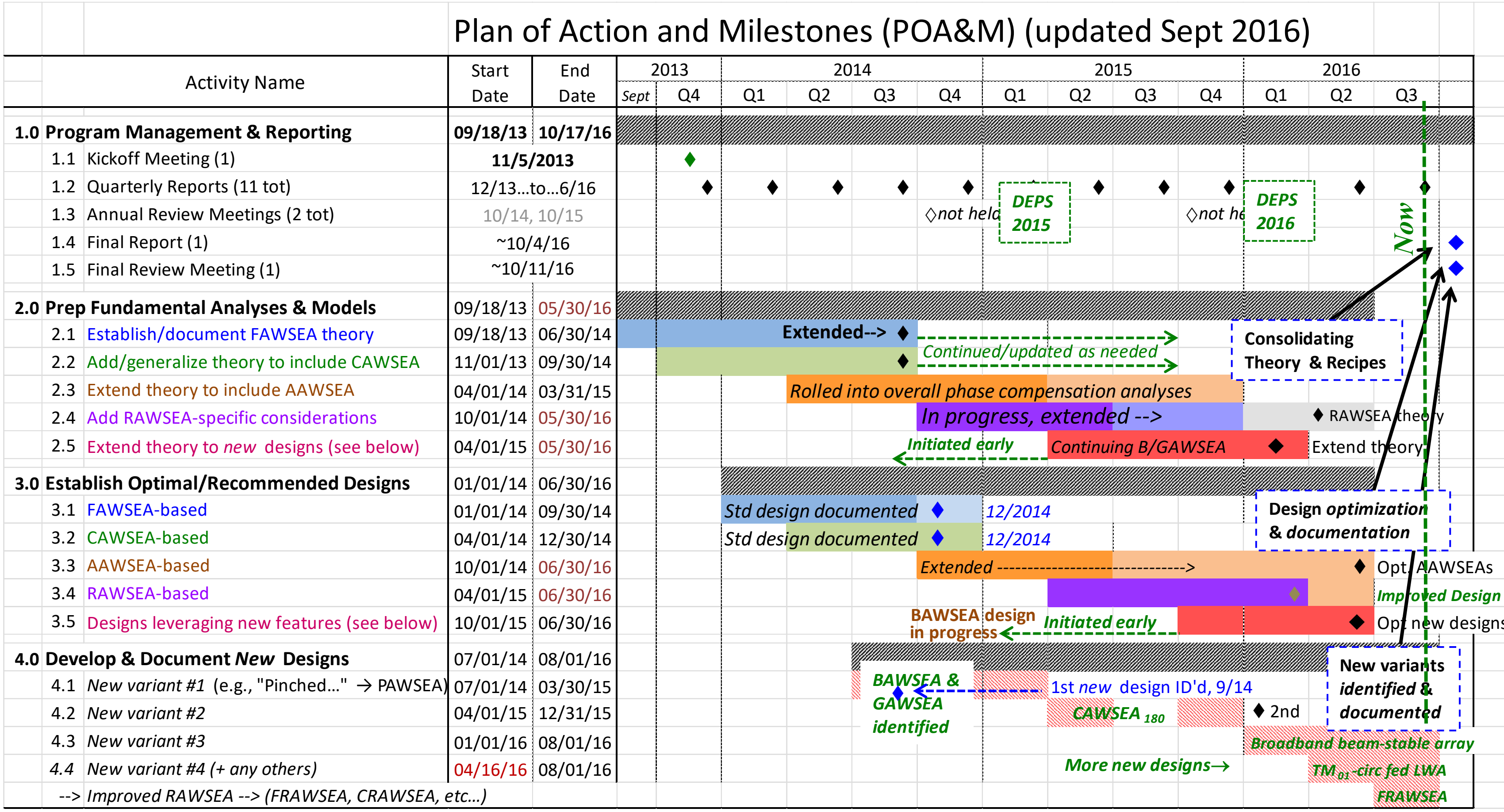

Figure 1. Updated Program Plan

3. RESEARCH AND ACTIVITIES PERFORMED THIS PERIOD

3.1. Development of an Improved-design Flat RAWSEA (FRAWSEA)

Figure 2 compares cross-sections for three versions of four-channel leaky-wave antennas with flat apertures, all designed to the same center-frequency and shown on the same size scale. The *rotated* (the "R" in "RAWSEA") channels in the middle and right panels of the figure reduce the depth of the antenna compared to the non-rotated (FAWSEA) version.

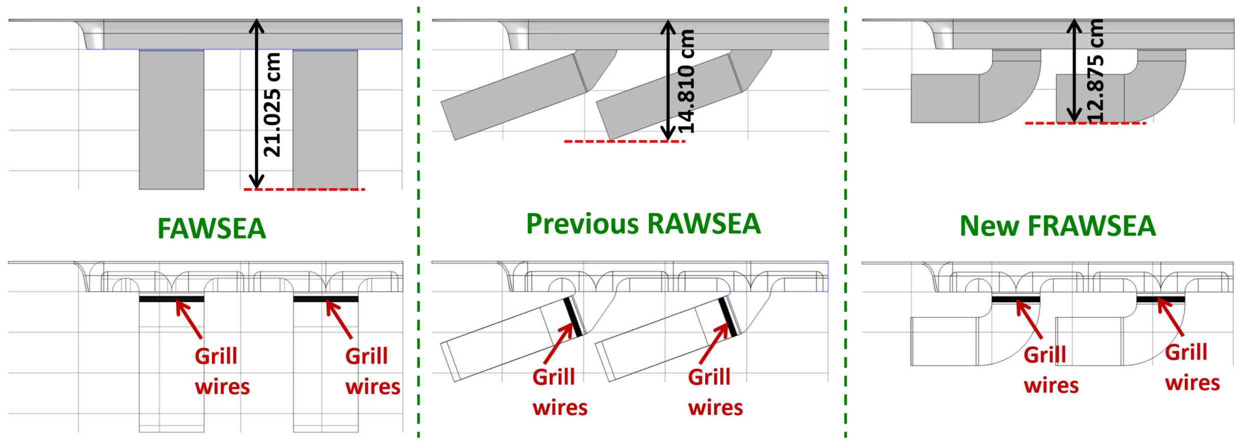

Figure 2. Cross-sections, shown to scale in solid and transparent views, for 4-channel flat-aperture designs with f_0 = 1.0 GHz. Only half of each cross-section (two channels) is shown. Left: FAWSEA. Middle: Previous RAWSEA design. Right: New FRAWSEA.

Our earlier RAWSEA concept had its basis in SARA R&D supported by AFRL, in late 2012. At that time, we rotated the leaky grill-wire plane along with the leaky-wave channel (see middle panel, bottom). This conveniently maintained the rectangular cross-section of the leaky channel but increased the separation of the window interface from the grill-wire plane, introducing a quasi-free space transition section (the bend region). This ultimately complicated the theoretical analyses and design of the leaky wire grill (see Quarterly Report #7). Although the antenna depth was substantially reduced, maintaining high aperture efficiency required placing the channels too close together to achieve a full 90º rotation of the channels. In contrast, with the new FRAWSEA configuration shown in the right-hand panel, the leaky wire grill is returned to its original FAWSEA-type position very near the window interface, while the bend (curved region) of the channel becomes explicitly part of the leaky waveguide, which allows us to reduce the lateral extension of the rotated channel for a given cutoff frequency. In fact, this change now means it is small enough to rotate the full 90º without bumping against an adjoining channel. And that yields the *lowest-profile configuration to date*. Not only that, but if the depth of the leaky channel is chosen carefully, the leaky wire grill algorithms used for defining the FAWSEA wire grill can now also be applied here, with minimal modification. The operating mode in the leaky guide is fundamental mode, with the field lines mapped to conform to the new cross-section. The quasi-free space region that complicated the interaction of the grill and window is now eliminated. The new FRAWSEA cross-section in Figure 2 (right), is <u>less than 0.43 λ_0 thick</u>.

In exchange for this packaging advantage, one must address the following: (1) the leaky waveguides do not present simple rectangular cross-sections for connection to the antenna, and (2) there is some new field enhancement internally in the waveguide structure along the smaller radius of the cross-sectional bend. The former can be addressed by means of a custom transition section (which we will discuss shortly) added to the feed, to provide a rectangular guide. The aforementioned field enhancement does not appear to be serious in our candidate configurations; rather, external air breakdown continues to define the upper bound to the overall peak-power handling.

We have prepared 3D RF models and predicted performance curves for our suggested/recommended FRAWSEA design, leveraging this new cross section. We are pleased to report that it works (in numerical models) fairly well, so this new design once-again expands the catalog of antenna geometries identified and documented under this R&D program. Figure 3 shows views of an example *single-channel* FRAWSEA, from a 3D RF model. The key parts of this example are usable as building blocks for an array, in much the same way as was done with our FAWSEA designs documented earlier.

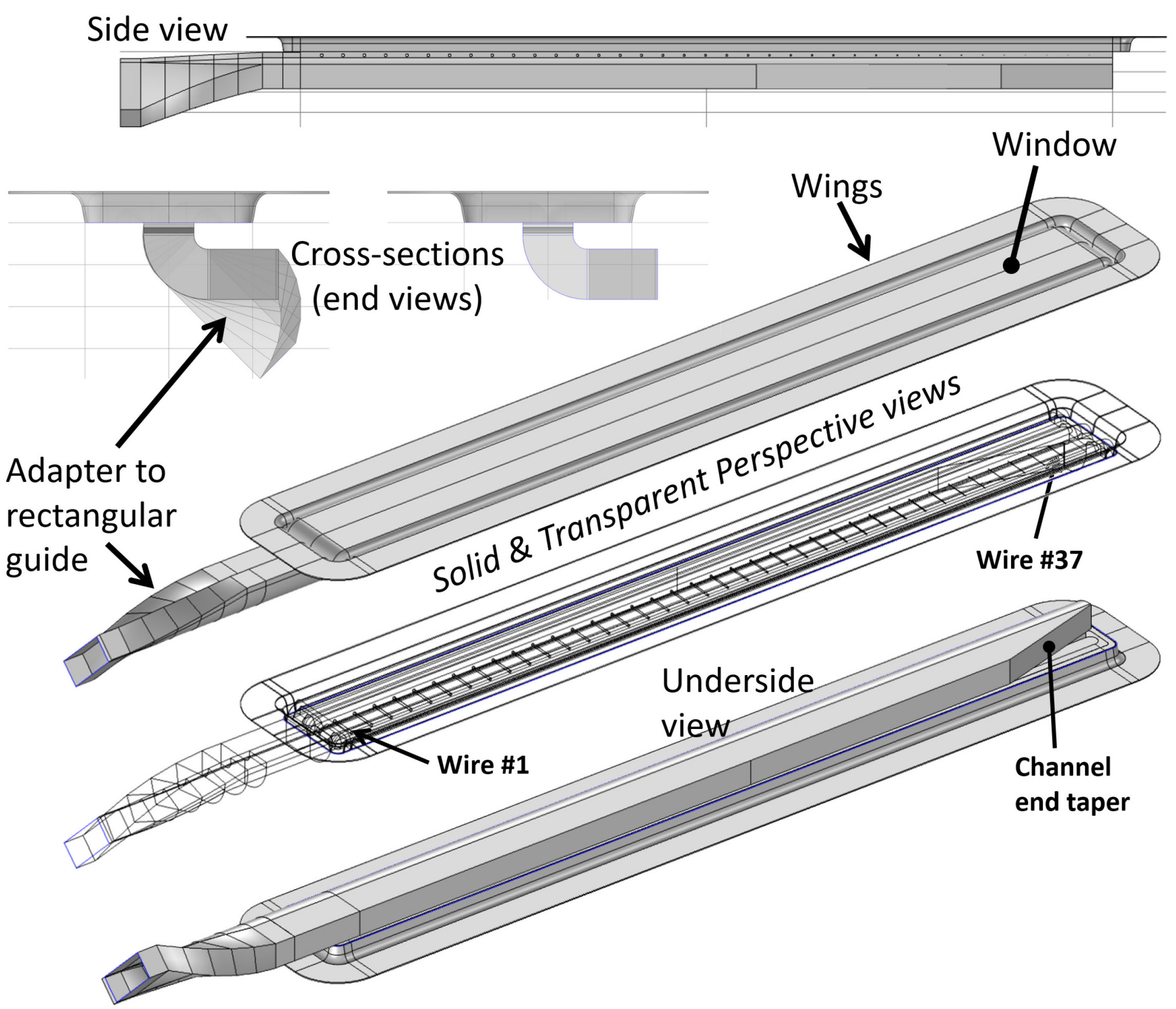

Figure 3. Views of a single-channel FRAWSEA, including a waveguide tapered transition/adapter to facilitate a practical connection to a rectangular waveguide.

As with the FAWSEA, an array (a multi-channel FRAWSEA) can be prepared by including appropriate channel-to-channel spacing, joining channels judiciously, extending the aperture window to span multiple channels, and revising the wings to fit around the overall wider aperture. Arrays with either *translational* or *mirror* symmetry employing such rotated channels are possible. The proper choice depends on what is most convenient for packaging and interfacing to the HPM source of interest. It should go without saying that care should be taken in setting the field-orientations at the input, so that the waves at the leaky walls of the individual channels are properly in phase at the aperture; embarrassing errors are easily avoidable by diligently following along the waveguide curves. A four channel FRAWSEA (with mirror symmetry, in this case) is shown in Figure 4, and is hereby denoted a "suggested/recommended" design. Just as with the other antennas studied in this R&D, a wide variety of sizes and aspect ratios are possible.

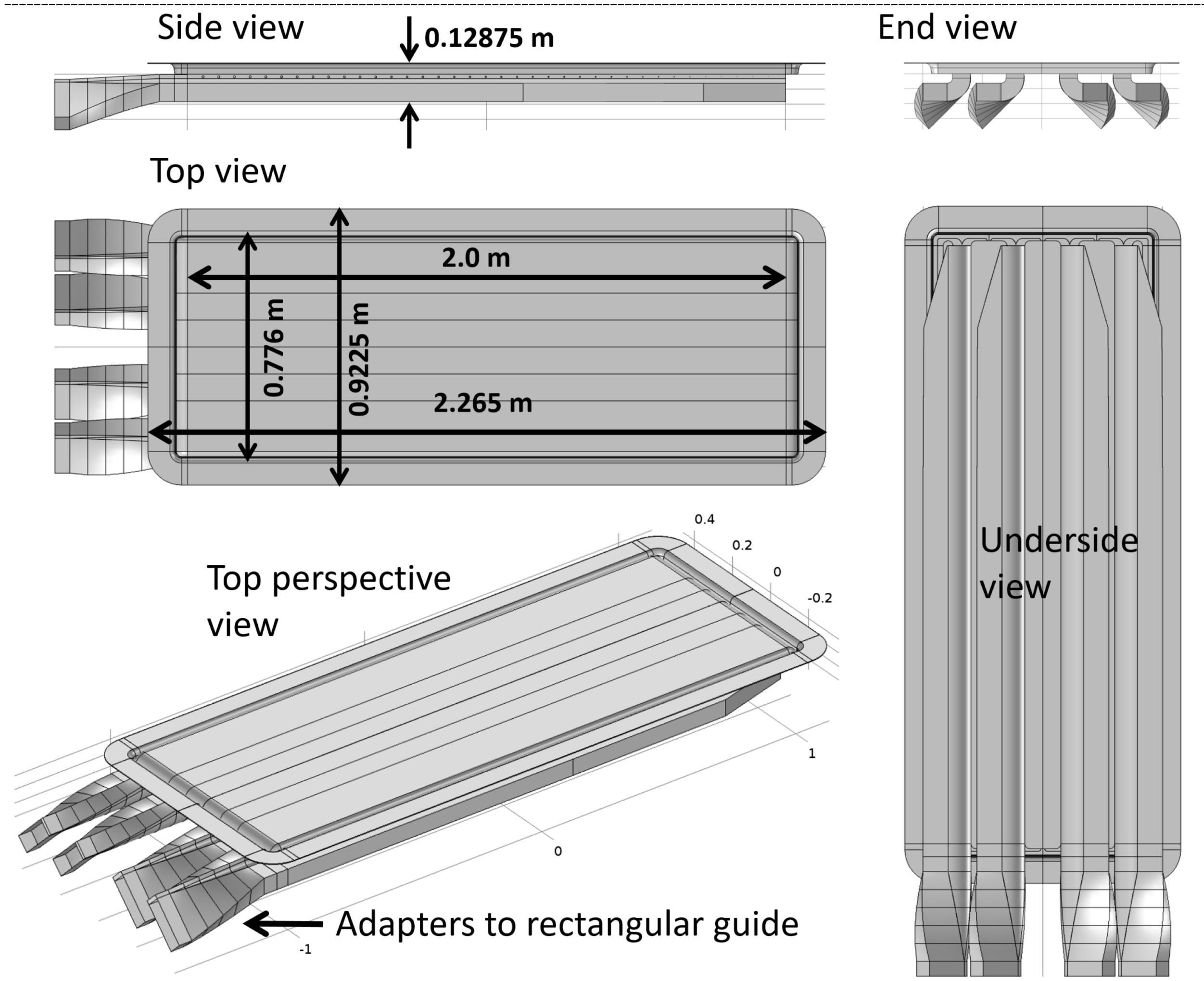

Figure 4. Example four-channel FRAWSEA designed for f_0=1.0 GHz and employing mirror-symmetric feeds. Tapered waveguide transitions/adapters are used to allow practical connection of the antenna to rectangular waveguides.

Figure 5 tabulates diameters and positions for the 37 wires comprising the leaky-grills of the FRAWSEAs in Figure 3 and Figure 4. Wire sizes were derived from the FAWSEA wire-grill generation routines, but the last few values (#s 35-37) were replaced with those from wire #34. This helped to reduce (but did not eliminate)

FRAWSEA wire grill info. Grill wire centers are at -.91 cm vert from top of chan.

Grill wire index	Distance along the aprtr (cm)	Grill wire dia (mm)	*...continued:* Grill wire index	Distance along the aprtr (cm)	Grill wire dia (mm)	*...continued:* Grill wire index	Distance along the aprtr (cm)	Grill wire dia (mm)
1	5.25	7.010						
2	10.50	6.918	14	73.50	5.530	26	136.50	3.183
3	15.75	6.823	15	78.75	5.382	27	141.75	2.907
4	21.00	6.725	16	84.00	5.229	28	147.00	2.613
5	26.25	6.624	17	89.25	5.068	29	152.25	2.299
6	31.50	6.519	18	94.50	4.899	30	157.50	1.966
7	36.75	6.411	19	99.75	4.723	31	162.75	1.612
8	42.00	6.299	20	105.00	4.537	32	168.00	1.240
9	47.25	6.182	21	110.25	4.341	33	173.25	0.859
10	52.50	6.062	22	115.50	4.135	34	178.50	0.489
11	57.75	5.937	23	120.75	3.917	35	183.75	0.489
12	63.00	5.806	24	126.00	3.687	36	189.00	0.489
13	68.25	5.671	25	131.25	3.443	37	194.25	0.489

Figure 5. Grill wire diameters and locations along leaky grill.

a tendency to form a hot spot (high E) on the aperture near the termination end of the channel. We also found it helpful to use a more aggressive taper at the channel end (see the underside view in Figure 3) than we would normally employ for a comparable FAWSEA. Computed patterns for the antenna in Figure 4 (which includes the feed adapters) at $f = 0.9\ f_0$, $1.0\ f_0$, and $1.05\ f_0$, are shown in Figure 6.

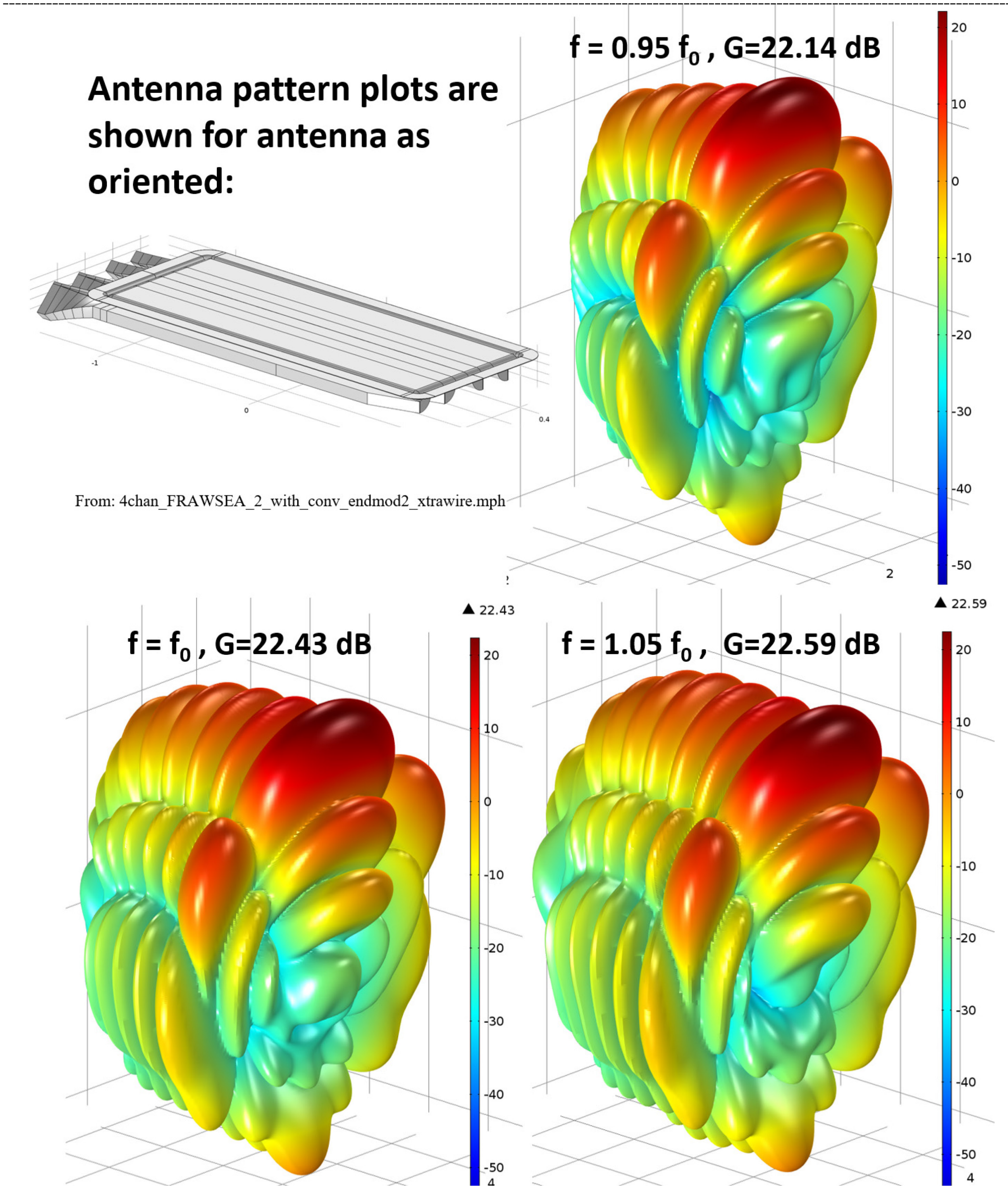

Figure 6. Computed 3D antenna patterns, four-channel FRAWSEA at three frequencies.

Some important performance characteristics for this FRAWSEA vs. frequency are shown in Figure 7.

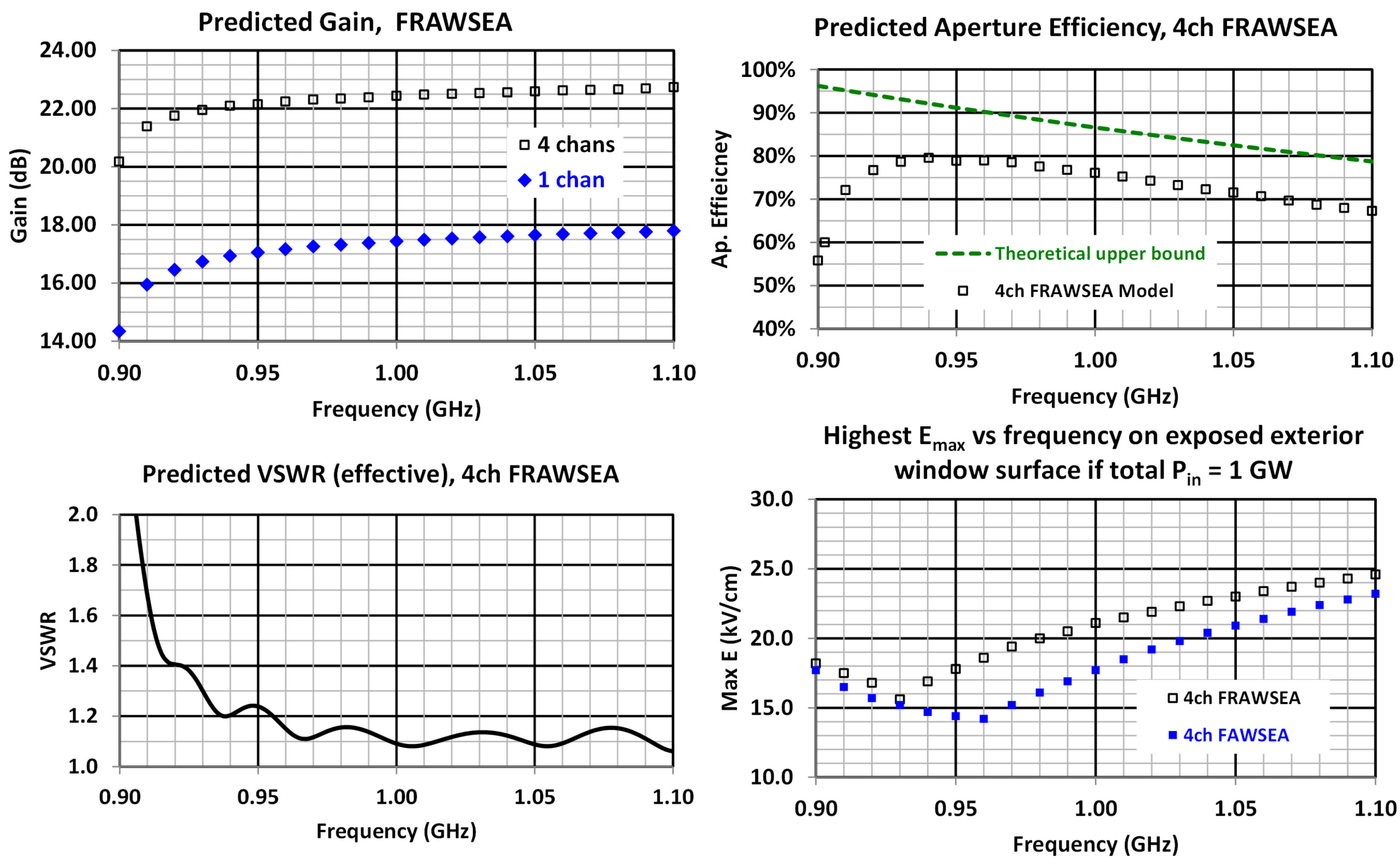

Figure 7. Predicted performance vs. frequency for the 4-channel FRAWSEA (includes waveguide adapters) of Figure 4.

The curves in Figure 7 compare quite respectably to those of our other suggested/recommended leaky-wave designs in terms of gain, bandwidth, and more. A more detailed comparison, to include all the other antennas, will be included in the Final Report. The beam tilt angle relative to the aperture normal likewise follows the theoretical curve fairly well (see Figure 8), though not quite as perfectly as our standard/recommended FAWSEA. Figure 9 provides a comparison of polar plots taken in the E and H planes at $f=f_0$, for a FAWSEA and FRAWSEA of essentially the same aperture dimensions. The pattern differences are very small. Although it is subtle to see from these plots, the FRAWSEA beam is tilted at a 29.37° angle relative to the normal, rather than at 30.0° like the FAWSEA, and the FRAWSEA delivers ~0.37dB less gain.

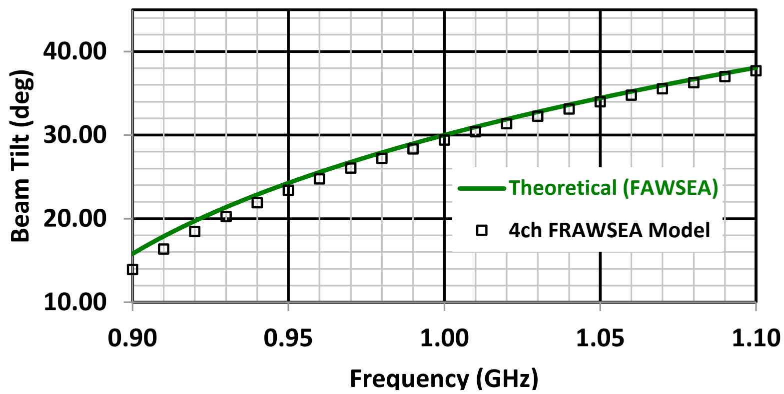

Figure 8. FRAWSEA Beam tilt vs. Frequency

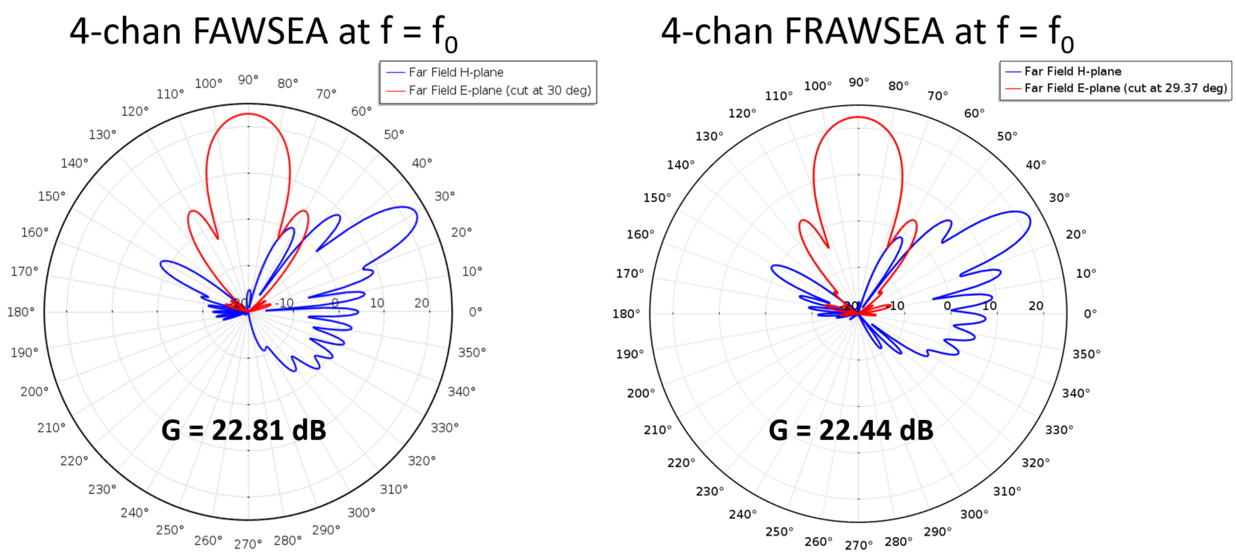

Figure 9. Polar E- and H-plane pattern cuts at $f=f_0$ for our recommended 4-channel FAWSEA (left) vs. the new recommended 4-channel FRAWSEA (right). (Same scale.)

An observant reader, if comparing some of the plots above to those in our earlier reports, may note that there are also some other minor or moderate differences between the new FRAWSEA and a comparable-aperture FAWSEA. Some, but not all of these differences arise from the waveguide adapter/transition sections added to the FRAWSEA. The rest we attribute mostly to the field distributions in the leaky waveguide incident at the wire-grill being somewhat less than ideal, mostly due to the wave passage around the bend immediately adjacent to that wire-grill interface. Regardless, considering its excellent predicted performance overall, the new FRAWSEA represents an option that should be seriously considered when an especially low-profile high-gain HPM-capable antenna is needed.

4. DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

Our work during the 12th quarter of the R&D program began with a goal of updating and making more practical the analyses and optimization of RAWSEAs, but evolved into development of a significantly improved design. The new design provides a shallower-depth overall and excellent performance, while at the same time features a more easily-optimized combination of leaky wire grill and window/interface. By returning the leaky wire grill to its original (per the FAWSEA) location, realization of effective channel rotation (and antenna depth reduction) becomes relatively straightforward to implement in both the flat and variously-curved configurations studied under this program. With that in mind, we suggest simply adding an "R" as part of the names of these antennas as follows, if/when they incorporate this feature:

Recommended Update to the Naming of these Antennas:

Original Nomenclature	If the channels are rotated	Aperture curvature type[1]
FAWSEA	FRAWSEA	Flat
CAWSEA	CRAWSEA	Curved
BAWSEA	BRAWSEA	Bent
AAWSEA	ARAWSEA	Arched
PAWSEA[2]	PRAWSEA	Pinched
GAWSEA	GRAWSEA	Generalized (multi-type)

RAWSEA ← Obsolete. Use one of the newer, more-specific, terms in the second column above.

This is the last of the Quarterly Reports for this program. It will be followed shortly by our Final Report, to be submitted to ONR next month. We are pleased with what we have accomplished under this R&D program during the last three years, which has included the discovery, design, analyses, improvement, and documentation of a variety of HPM-capable, forward-traveling wave, leaky-wave antennas, as well as identification of some interesting technology spinoffs. It is clear that there still remain many interesting avenues of exploration within the subject of "Low-Profile Leaky-Wave HPM Antennas." We look forward to those future investigations and hope to contribute to them.

We appreciate ONR's support for this R&D.

[1] These geometry types have been defined in our earlier reports; they will be discussed again in the Final Report.
[2] A special combination of *curved*, *arched*, and *bent*, intended specifically to conform to an ogive.

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